Journal of Physics: Conference Series

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To cite this article: L T Tran *et al* 2017 *J. Phys.: Conf. Ser.* **777** 012037

IOP Conf. Series: Journal of Physics: Conf. Series **777** (2017) 012037 doi:10.1088/1742-6596/777/1/012037

3D silicon microdosimetry and RBE study using ^{12}C ion of different energies

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Abstract. This paper presents a new version of the 3D mesa “bridge” microdosimeter comprised of an array of 4248 silicon cells fabricated on 10 μm thick silicon-on-insulator substrate. This microdosimeter has been designed to overcome limitations existing in previous generation silicon microdosimeters and it provides well-defined sensitive volumes and high spatial resolution. The charge collection characteristics of the new 3D mesa microdosimeter were investigated using the ANSTO heavy ion microprobe, utilizing 5.5 MeV He^{2+} ions. Measurement of microdosimetric quantities allowed for the determination of the Relative Biological Effectiveness of 290 MeV/u and 350 MeV/u ^{12}C heavy ion therapy beams at the Heavy Ion Medical Accelerator in Chiba (HIMAC), Japan. The microdosimetric RBE obtained showed good agreement with the tissue-equivalent proportional counter. Utilizing the high spatial resolution of the SOI microdosimeter, the LET spectra for 70 MeV $^{12}C^{+6}$ ions, like those present at the distal edge of 290 and 350 MeV/u beams, were obtained as the ions passed through thin layers of polyethylene film. This microdosimeter can provide useful information about the lineal energy transfer (LET) spectra downstream of the protective layers used for shielding of electronic devices for single event upset prediction.

1. Introduction

Heavy ions deposit energy in matter much differently to X-rays, depositing most of their energy near the end of their range, commonly known as the Bragg peak (BP). This characteristic is advantageous for radiotherapy as the highest dose can be delivered to the target volume with much lower doses to the surrounding healthy tissue. The energy deposition mechanisms of heavy ions in matter differ greatly to those of electrons or photons, especially their interactions with target nuclei which can contribute substantially to the delivered dose via nuclear fragmentation. In order to accurately predict damage in electronic devices or radiobiological effects in humans, whether it be in a space radiation environment or in cancer therapy, it is important to understand how the ion LET varies with depth, in addition to its relative biological effectiveness (RBE).

An effective approach for measuring the LET spectra and deriving the RBE for an ion beam is microdosimetry [1]. Microdosimetry is a method of measuring the microscopic pattern of ionizing energy deposition in a micron sized sensitive volume (SV) of similar dimensions to biological cells [2]. This technique is extremely useful for dosimetry in unknown mixed radiation fields typical of space and aviation, as well as in hadron therapy. The gold-standard detector used for microdosimetry is the tissue equivalent proportional counter (TEPC) which is advantageous due to its spherical sensitive volume and tissue equivalency through use of a tissue-equivalent gas. However, TEPCs have several limitations such as high voltage operation, large size of assembly, which reduces its spatial resolution as well as the wall effect [3] and an inability to simulate multiple cells.

The Centre for Medical Radiation Physics (CMRP), University of Wollongong, has initiated the concept of silicon microdosimetry to address the shortcomings of the TEPC [4, 5]. The latest development of SOI microdosimeters at CMRP is the 3D-mesa Bridge microdosimeter, produced by etching the silicon surrounding the SVs whilst leaving thin silicon bridges between them to support the aluminium tracks. However, in the original Bridge microdosimeter (BridgeV1), due to the remaining un-etched silicon, some low energy events were still observed [6].

Presented in this paper, is an improved 3D Bridge microdosimeter (BridgeV2) with fully etched silicon outside of the SVs down to 10µm depth. A charge collection study on this improved device and its application for lineal energy measurement and RBE determination using therapeutic 290 and 350 MeV/u ^{12}C ion beams at HIMAC, Japan are presented. Finally, to demonstrate its ability to measure lineal energy spectra of ions in matter with spatial resolution of the order of microns, the microdosimeter was irradiated with 70MeV carbon ions (180µm range in polyethylene) at the heavy ion accelerator facility at the Australian National University (ANU). The small range of these ions is particularly relevant to SEU prediction in packaged devices and their low energy provides conditions for minimal nuclear interactions, allowing RBE determination of a ^{12}C beam with minimal fragments.

2. Method

The BridgeV2 microdosimeter has the same design as the BridgeV1 except that the silicon in etched
regions is totally removed using plasma etching which produced parallelepiped sensitive volumes with walls perpendicular to the SiO_2 layer. In addition, using phosphorus ion implantation, an N^+ stop layer was created under the contact pads and on the top and sides of the silicon bridges to eliminate charge collection underneath the aluminium pads, as observed with version 1.

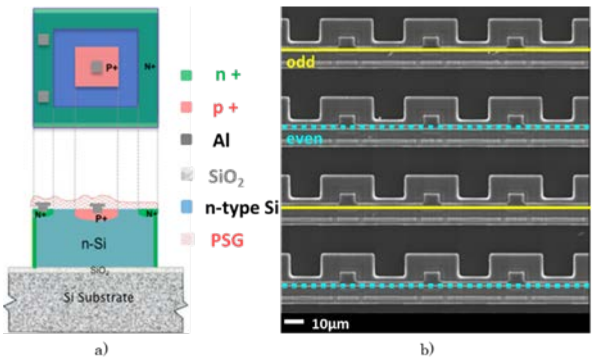

Figure 1. a) Plan and cross-section design schematics of a single BridgeV2 Microdosimeter SV and b) scanning electron microscope image showing the odd and even arrays of SVs, distinguished with solid and dashed lines, respectively.

The 3D Bridge microdosimeter has a large sensitive area with a die size of 4.1 x 3.6 mm^2, designed for use in low dose rate environments such as those in aviation and space. The microdosimeter is based on an array of planar 30 x 30 x 10 µm SVs fabricated on a high resistivity 3 kΩ.cm n-SOI active layer of thickness 10 µm and low resistivity supporting wafer. Each SV was fabricated using ion implantation to produce the square p-n junction structure. The even and odd rows of SVs are read out independently to avoid events in adjacent sensitive volumes being read out as a single event in the case of oblique charged particle tracks or delta electrons from energetic heavy ions typical of a galactic cosmic ray (GCR) environment. Figure 1 shows a simplified cross-section of the BridgeV2 microdosimeter.

The charge collection for the BridgeV1 and BridgeV2 microdosimeters was investigated using the ion beam induced charge collection (IBICC) technique with the heavy ion microprobe at the ANSTO [7]. A 5.5 MeV microbeam of He^{2+} ions focused to a diameter of approximately 1 μm was raster scanned over the surface of the microdosimeter. For a single energy deposition event occurring in the microdosimeter, the beam position (X,Y) and energy deposited E was recorded and used to create median energy maps, allowing the charge collection in the device to be observed visually.

The improved bridge microdosimeter was irradiated at HIMAC facility in Japan with 290 MeV/u and 350 MeV/u corresponding to a total energy of 3.48 GeV and 4.2 GeV, respectively. The microdosimeter was placed in various positions along the central axis of 60 mm Spread Out Bragg Peak (SOBP). A modular polymethyl methacrylate (PMMA) phantom was used to adjust the position of the BP relative to the device with 0.5 mm increments. The microdosimeter response was also measured along the BP produced by 70 MeV carbon ions in low density polyethylene (LDPE) at ANU, Canberra. The measurements were carried out in vacuum with different thicknesses of LDPE foils placed in front of the microdosimeter with 10 μm increments at the end of the ion range.

3. Results

Figure 2a shows a magnified scanning electron microscope (SEM) image of a single SV of the BridgeV1 microdosimeter. It can be seen that the 3D SV has a truncated square pyramid shape due to different etching times along the SVs depth. The top layer above the SVs is the SiO2 and Phosphor Silicate Glass (PSG) layers with original size of 30 μm x 30 μm which has not been removed due to selective etching. Figure 2b shows an SEM image of an array of SVs in the BridgeV2 microdosimeter where the surrounding silicon has been fully etched down to 10 μm depth with a straight parallelepiped shape. This technique provided well-defined geometry of micron-sized semi-3D SVs as in the design (Figure 1a).

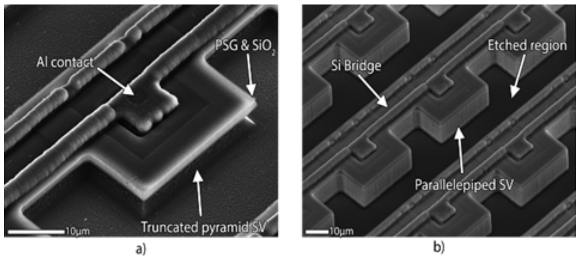

Figure 2. SEM images of the a) BridgeV1 and b) BridgeV2 microdosimeter.

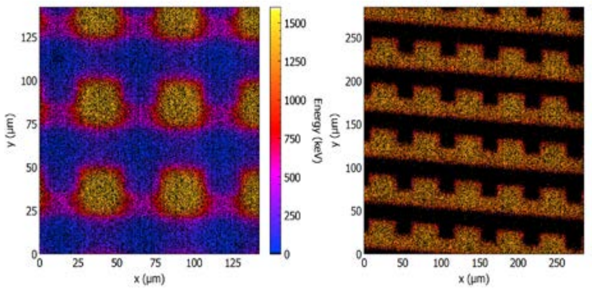

Figure 3. Median energy map showing the response of the 3D Bridge microdosimeters V1 (left) and V2 (right) to 5.5 MeV He2+ ions.

Figure 3 show the median energy map obtained from odd and even arrays of the BridgeV2 microdosimeter. The microbeam was scanned across the microdosimeter using a scanning area of 0.3 mm x 0.3 mm with the microdosimeter biased at -10 V. Figure 3 right shows nearly full charge collection in the 30x30x10 μm^3 SVs. Due to high resistivity of n-Si, charge collection is observed in the thin bridge regions between the SVs.

Using the Microdosimetric Kinetic Model (MKM) [8] and microdosimetric spectra obtained with the BridgeV2 microdosimeter, the RBE_{10} values were derived along the central axis of the 60 mm SOBP 290MeV/u ^{12}C beam, seen in Figure. 4. The RBE_{10} values match very well with those obtained from the TEPC measurements. Due to the high spatial resolution of the microdosimeter, a more detailed RBE_{10} distribution was obtained at the end of the SOBP compared to the TEPC. It should be noted that the BridgeV2 microdosimeter measurements were done in a PMMA phantom while the TEPC measurements were carried out in water, hence range scaling has been used to match the results.

Microdosimetric spectra measured with the BridgeV2 microdosimeter at the distal part of the 290MeV/u SOBP at HIMAC and at the end of the BP for 70 MeV ^{12}C ions at ANU are presented in Figure 5. Figure 5 shows the microdosimetric spectra obtained with the BridgeV2 in response to 290 MeV/u SOBP and 70 MeV ^{12}C. In the case of the 290 MeV/u SOBP beam, the microdosimetric spectrum is enhanced by nuclear fragmentation while in the case of the 70 MeV ^{12}C ions, the microdosimetric spectrum was produced by carbon ions only, with negligible contribution from fragementation and neutrons due to low energy ions. In both cases, the BridgeV2 microdosimeter was placed at the end of the SOBP/BP with high $\overline{y_D}$, however the shape of the microdosimetric spectra differs greatly. This is explained by much higher straggling of 290 MeV/u carbon ions travelling through 129 mm of PMMA (approximately their range in PMMA) in contrast to 70 MeV ions traversing only 180 µm in LDPE (approximately their range in LDPE). For measurements with 70 MeV carbon ions the microdosimeter was able to measure at the end of the carbon BP with 10 µm depth increments while mesurements were done with 0.5 mm depth increments for the 290 MeV/u beam. These results have demonstrated the BridgeV2 microdosimeters extremely high spatial resolution and ability to detect pecularities in ion LET within extremely thin layers of shielding material, relevant for space application and shielding verification.

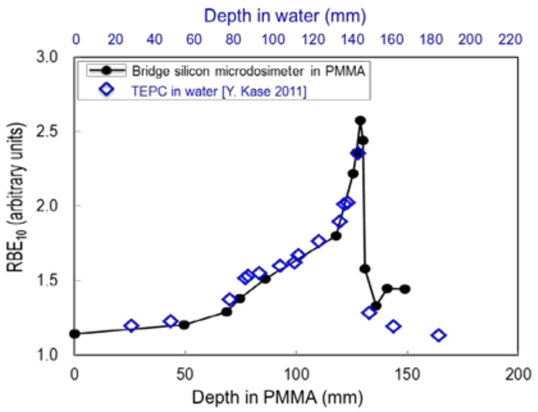

Figure 4 Derived RBE$_{10}$ values along the central axis of the 60 mm SOBP ^{12}C beam, obtained with the BridgeV2 microdosimeter and TEPC at NIRS.

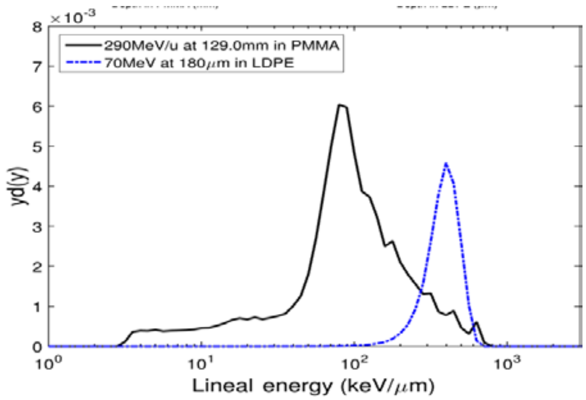

Figure 5 Microdosimetric spectra measured using the BridgeV2 microdosimeter with 290 MeV/u 60mm SOBP ^{12}C beam at 129 mm in PMMA (solid line) and 70 MeV ^{12}C ions at 180 µm LDPE film (dashed line).

4. Conclusion

The new CMRP 3D bridge microdosimeter was investigated in detail using scanning electron microscopy and 5.5 MeV He^{2+} microbeams. The silicon surrounding the SVs was totally etched down to the SiO_2 layer which provided well-defined SVs and substantially reduced the charge sharing between the SVs. This work presented the RBE$_{10}$ derivation in a ^{12}C ion therapeutic beam using a high spatial resolution SOI microdosimeter. The obtained RBE$_{10}$ values were found to be in good agreement with values obtained using a TEPC, with an exception at the distal part of the SOBP where spatial resolution of TEPC was not enough in comparison with the SOI microdosimeter and this requires a further investigation. Additionally to this discrepancy, the TEPC measurements being carried out in water which lacks the C atoms in contrast to PMMA.

This work also presented the first study of application of the developed bridge microdosimeter for LET measurement of low energy ion in different depths of an absorber with 10 µm spatial resolution. It is important for improvements of Monte Carlo simulation for shielding and coating for electronic devices and RBE studies at the distal part of the ^{12}C BP which have never been studied before with such high spatial resolution.

5. References

[1] ICRU 1983 *Report 36* (ICRU: Bethesda, MD)
[2] Rossi H and Zaider M 1996 *Microdosimetry and its Applications* (Springer: London)

[3] Bradley P D *et al* 1998 *IEEE Trans. Nucl. Sci.* **45** 2700-2010
[4] Bradley P D PhD thesis 2000 University of Wollongong, Australia
[5] Cornelius I M *et al* 2003 *IEEE Trans. Nucl. Sci*. **50** 2373-79
[6] Tran L T *et al* 2015 *IEEE Trans. Nucl. Sci*. **62** 504-11
[7] Siegele R *et al* 1999 *Nucl. Instrum. Methods Phys. Res. B* **158** 31-8
[8] Kase Y *et al* 2006 *Radiat. Res*. 166 629-38